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Southwestern Patagonia and Their Possible Effects on Giant Kelp Forests

A. Mora-Soto, C. Aguirre, J. L. Iriarte, M. Palacios, E. C. Macaya, M. Macias-Fauria

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A Song of Wind and Ice: Increased Frequency of Marine Cold-Spells in Southwestern Patagonia and Their Possible Effects on Giant Kelp Forests

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Key Points:

- In Southwestern Patagonia, multiple extreme cold-spells have occurred in the decade of 2010–2020
- New potential stressors related to these extreme cold events include glacier meltwater and increased storm activity
- This research confirms observed trends of a cooling Southern Ocean, pointing out the need for studies at smaller scales in complex coastal areas

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract In contrast to other coastal regions of the world, the giant kelp (*Macrocystis pyrifera*) ecosystem in southwestern Patagonia has been persistent in area and associated biodiversity in the last decades. In this ecoregion, sea surface temperature (SST) records have consistently remained below the upper thermal threshold for kelp survival, however, no studies have analyzed the spatiotemporal variability of SSTs and their anomalies across the geographical diversity of the southwestern Patagonian coastline. We explored the geographical distribution of extreme warm and cold events in this region from latitudes 47°–56°S in a range of ~1,000 km, identifying the dates and spatial distribution of marine heatwaves (MHWs) and marine cold-spells (MCSs) from 1982 to 2020. Results show that a peak in the number of MHWs occurred in the great El Niño year of 1998. Additionally, the 2014–2019 period has had more severe and extreme MCSs than the previous decades. We discuss the origin of these events with a focus on three main processes: (a) geographically constrained cold events caused by glacier melting, (b) regional cold events caused by extreme winds linked to the position of the polar front, and (c) extensive SST anomalies linked to planetary-scale events such as El Niño and La Niña. Overall, those processes were conducive to counteract global warming trends locally/regionally, highlighting southwestern Patagonia as a possible climatic refugium for the giant kelp ecosystem. Despite this, the effects of freshwater inputs and storm turbulence on the exposed coasts facing the Southern Ocean may cause new kinds of stress on this ecosystem.

Plain Language Summary The western Patagonian coastline is habitat for one of the largest extents of the giant kelp ecosystem on the planet. The persistence of this ecosystem adapted to temperate-to-cold sea temperatures in this area may be explained by the absence of extreme marine heatwaves. In this research, we characterized the frequency, intensity, and duration of marine heatwaves (MHWs) and marine cold-spells that occurred between 1982 and 2020, using information derived from satellites. These data provide sea surface temperatures for all the area of study. We confirmed that there were no extreme MHWs reaching stressing temperatures for giant kelp during the period we analyzed, which spans the longest continuous record available employing satellite data. Moreover, the last decade experienced extreme cold events in the coasts near the fjords and in the extreme south of the continent. In the current scenario of climate change, western Patagonia could be a climate refugium for giant kelp. We further identify glacier melt and increased turbulence in the sea due to increased storminess as emerging stressors of this ecosystem.

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1. Introduction

Increased evidence in the last decade has shown that the world ocean has been warming with more frequent and intense marine heatwaves (MHWs). These climatic events, sensu Hobday et al. (2016), are defined as discrete prolonged anomalously warm water events in a particular location. A flourishing corpus of methodologies and

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analyses has arisen in the last years to explain their causes, signaling blocking high-pressure systems, oceanic oscillations such as El Niño events, and shifts in winds and currents, as well as their disturbance effects on foundation species such as corals, seagrasses, and kelp forests (Holbrook et al., 2020).

Globally, kelp forest ecosystems—adapted to temperate to cold temperatures—are experiencing the direct and indirect effects of ocean warming (Graham et al., 2007; Wernberg et al., 2019). MHWs, particularly in Australia and California-Mexico, have caused catastrophic consequences in those foundation species and associated ecosystems, such as decreased abundances in number of individuals and community species (Arafteh-Dalmau et al., 2019; Cavanaugh et al., 2019; Ramírez-Valdez et al., 2017), contraction of the historical range distributions (Wernberg et al., 2016, 2013), increased grazing from herbivorous fish and sea urchins (Rogers-Bennett & Catton, 2019; Vergés et al., 2014), and/or competition with invasive species, such as turf-forming algae (Filbee-Dexter & Wernberg, 2018).

So far, however, there are no reports of climate-driven changes in the kelp forests of the northern and central Chilean coasts (see a global review in Smale, 2019), dominated by constant upwelling of cold and nutrient-rich waters. Nevertheless, oceanic oscillations such as El Niño Southern Oscillation (ENSO) has caused local kelp extinctions and slow recovery in these coasts (Martínez et al., 2003; Vásquez et al., 2006) whereas some populations are under clear and direct pressures of anthropogenic origin, like kelp harvesting (Krumhansl et al., 2016; Márquez & Vásquez, 2020; Pérez-Matus et al., 2017; Vásquez, 2008; Vásquez et al., 2012).

Southern Chile (southwestern Patagonia, 41°–56°S) ocean waters have been less affected by MHWs in the period 1982–2016 than most regions in the world ocean (Oliver et al., 2018), with less frequency and duration (Marin et al., 2021) and less thermal displacement reported for these events (Jacox et al., 2020). Additionally, climate models show that this large region will experience less heat intensity than other areas of the ocean in the next century (Oliver et al., 2019). Forced upwelling and northwards cold-water advection by the Antarctic Circumpolar Current (ACC) have been proposed as causing such lack of warming trends (Armour et al., 2016; Oliver et al., 2019). Alternatively, internal ocean variability may be linked to a temporal hiatus over a general warming pattern (Marin et al., 2021).

In addition, marine cold-spells (MCSs) may also occur in the same coastal waters as MHWs, and have been associated with coastal upwelling enhancing primary production, as observed in the coastlines of South Africa and Western Australia (Feng et al., 2021; Schlegel et al., 2017). Global analyses have pointed out that MCSs have decreased in frequency and intensity in the last decades, except for the Southern Ocean, where the number of MCSs has increased (Schlegel et al., 2021). To our knowledge, no previous studies have investigated the frequency of MCSs in the Humboldt or the Cape Horn currents; moreover, no previous studies have investigated the location and intensity of MHWs and MCSs with a focus on the long and complex coastline of islands, channels, and fjords of Patagonia.

The coastline of this marine ecoregion, also known as Channels and Fjords of Southern Chile (Spalding et al., 2007), is conspicuously bordered by the least disturbed giant kelp forests on the planet (Dayton, 1985; Mora-Soto et al., 2021), which is one of largest extents of their global distribution in the sub-Antarctic latitudes (Mora-Soto et al., 2020). As any kelp species, *M. pyrifera* is adapted to cold-temperate environments, and water temperature is the most important driver of their performance, which is also negatively related with the presence of nutrients in the water column (Fernández et al., 2021, Graham et al., 2007).

A recent study carried out on giant kelp in the southernmost coast of Tierra del Fuego and Isla de Los Estados in 2018 compared densities, holdfast diameter of giant kelp, and ecological interactions with surveys performed in 1973 and found no significant differences (Friedlander et al., 2020). The observed marine biodiversity and long-term persistence of these forests give support to consider that these are one of the last intact ecosystems on Earth (Friedlander et al., 2018, 2021; Mora-Soto et al., 2021), and could be one of the last climatic refugia for this ecosystem. To evaluate this hypothesis, it is important (a) to determine the spatiotemporal variability of sea surface temperatures bordering the south of the continent, and (b) to propose the possible abiotic mechanisms that could explain the stability of this ecosystem.

The present study provides a geographical overview of warm and cold extreme SST events in southwestern Patagonia during the last four decades. Specifically, our aim is to outline the spatial patterns and trends of these thermal anomalies, in order to discuss their possible impacts on the giant kelp forests of this ecoregion. We

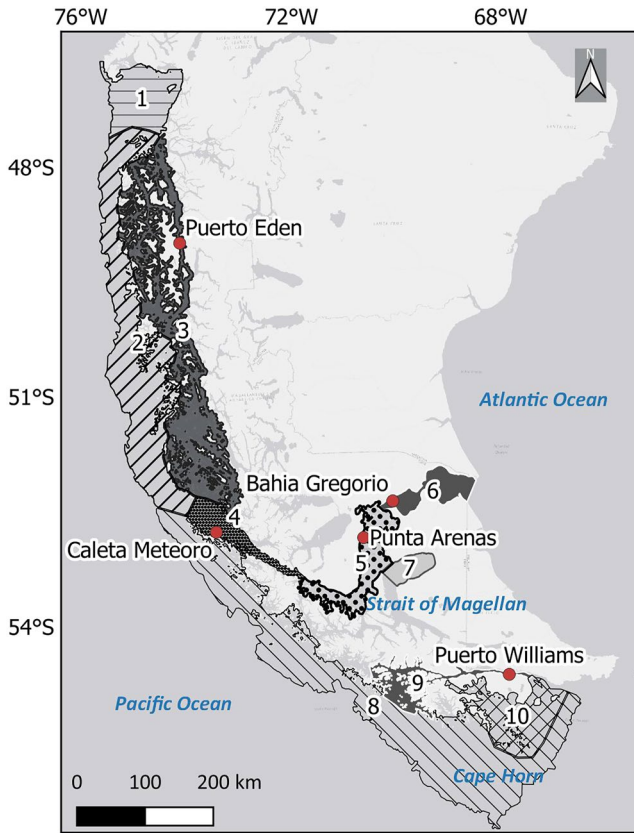


Figure 1. Map of the marine ecosystems mentioned in this study: (1) Gulf of Penas; (2) Offshore Kawésqar; (3) Nearshore Kawésqar; (4) Western Strait; (5) Central Strait; (6) Eastern Strait; (7) Bahía Inútil; (8) Offshore Magellan; (9) Nearshore Beagle Ballenero; (10) Nearshore Nassau Hornos. Red points indicate the location of the sea surface temperature (SST) in situ sensors. Background map: © OpenStreetMap contributors.

present the case of a kelp forest ecoregion—the largest on Earth in area for *M. pyrifera*—facing different MHW and MCS patterns than the rest of giant kelp populations of the world.

2. Materials and Methods

2.1. Area of Study

The area of study spans the marine ecoregion of Channels and Fjords of Southern Chile (Spalding et al., 2007), from Gulf of Penas to the Cape Horn archipelago (47°–56°S; ~1,000 km in a straight line) and a longitudinal range from the Pacific Ocean (75°W) to the eastern entrance of the Strait of Magellan (68°W). This southernmost continental land region outside of Antarctica is dominated by the southern Andes, which interacts with the year-long Southern Westerly Winds and is just north of the ACC. As a consequence, the western side of the Andes receives quasi-permanent strong westerly winds and annual rainfall accumulations that range from 6,000 to 7,000 mm at sea level, while the eastern side is under a rain shadow effect (Schneider et al., 2003). This land comprises the Northern and Southern Patagonian Ice fields and numerous glaciers, as well as Cordillera Darwin in Tierra del Fuego. Glaciers in the region show different rates of retreat, and even some advances (Bown et al., 2014; Dussaillant et al., 2019; Sakakibara & Sugiyama, 2014). The coastal geomorphology is characterized by the presence of fjords, channels, straits, and embayments; beyond the presence of giant kelp forests along the coastal border, the almost vertical deep underwater walls of the fjords are habitat for a high marine biodiversity including cold-water hydrocorals (Häussermann & Försterra, 2007).

Integrating previous studies and expert knowledge, Rovira and Herreiros (2016) subdivided this ecoregion into marine ecosystems, defined as spatial units encompassing similar areas of benthic depth, type of substrate, main geofoms, sea-coast interface, and ecological processes (Figure 1). From north to south, these are: *Gulf of Penas*, an exposed and turbulent area open to the Pacific Ocean; *Offshore and Nearshore Kawésqar*, in the archipelagos and fjords near the Southern Patagonian Ice Field; the *Western, Central, Eastern, and Bahía Inútil* sections of the *Strait of Magellan*; and the Magellanic areas, subdivided among *Offshore Magellan*, the *Nearshore Beagle Ballenero*, and the areas surrounding the Cape Horn at the end of the continent (*Nearshore Nassau Hornos*). Hence, we consider 10 main marine ecosystems covering 73% of the total Channels and Fjords ecoregion; we excluded smaller areas like inner fjords and sounds due to the lack of satellite-detected SST data, as well as the Atlantic side of this ecoregion (eastern Tierra del Fuego and Isla de Los Estados). We further limited our study area to a bathymetric range down to 200 m depth.

2.2. MHW and MCS Definition and Characterization

MHWs were defined as “a prolonged discrete anomalously warm water event that can be described by its duration, intensity, rate of evolution and spatial extent” as in Hobday et al. (2016). MCSs follow the same definition, except for being “anomalously cold water events” (Schlegel et al., 2017). These are identified when daily time series exceeds a threshold of the 90th (MHWs), or fall below the tenth percentile (MCSs), for more than 5 days. This is calculated using a running window of 11 days centered on the time of the year, where the mean and the threshold are calculated in a satellite-derived SST series for at least 30 years. In this study, we used the complete time series from 1 January 1982 to 31 December 2020. Further, MHWs (MCSs) are categorized as Category I, II, III, and IV when the local difference between the intensity of the MHWs (MCSs) and the climatological mean is one, two, three, or four times or more (less) than the climatological 90th (10th) percentile, respectively, using as reference the maximum intensity (I_{max}), which is specific to the location and time of the year where/when is

Table 1
Location of the In Situ Records

Name	Latitude	Longitude	Distance	Start date	Marine ecosystem
Bahia Gregorio	52°38'53"S	70°12'33"W	0 km	06-07-2014	Strait of Magellan East
Caleta Meteor	52°57'40"S	74°04'20"W	0 km	06-07-2014	Strait of Magellan West
Punta Arenas	53°07'25"S	70°51'43"W	0 km	06-02-2002	Strait of Magellan Central
Puerto Eden	49°07'47"S	74°24'31"W	95 km	22-10-2011	Nearshore Kawésqar
Puerto Williams	54°55'58"S	67°36'30"W	140 km	02-01-2000	Nearshore Beagle Ballenero

Note. Distance is the linear length between the in situ and the closest OISST record.

calculated. A detailed explanation on this method and classification is given by Hobday et al. (2016, 2018). We obtained SST measurements from the NOAA CDR OISST v02r01: Optimum Interpolation sea surface temperature (SST; Reynolds et al., 2008). This data set was elaborated with observations from ships and buoys and satellite observations, and corrected with an optimum interpolation analysis that accounts for irregularly spaced data. We extracted daily mean SST per *marine ecosystem* through zonal statistics, with a spatial resolution of 0.25 arc degrees, using a Google Earth Engine script (Gorelick et al., 2017). We found a gap of data between 31 December 1984 to 1 September 1985, and 31 December 2020, not included in the analysis.

The accuracy of satellite-detected SST data in the inner waters of Patagonia could be potentially lower than that in the open seas of the Southern Hemisphere (Reynolds et al., 2007). Furthermore, previous studies have warned about the importance of calculating the level of certainty and bias when using satellite-detected SST in coastal areas (Lee & Park, 2020; Smale & Wernberg, 2009; Stobart et al., 2015). To explore this, we compared OISST pixels with in situ automatic SST records from five sites covering five marine ecosystems of our area of study (Table 1). In situ data are collected every 2 min through VAISALA (HANDAR) platforms managed by the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA). Two of the five sites were located far (95 and 140 km) from any OISST pixel, whereas three out of the five stations were covered by OISST pixels. A Pearson's correlation and a linear model were applied comparing daily in situ/satellite records, as well as a root-mean-square errors (RMSE) and bias:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (A_i - B_i)^2}$$

$$\text{bias} = \frac{1}{n} \sum_{i=1}^n (A_i - B_i)^2$$

where A_i is the time series of the closest OISST pixel to the in situ record, B_i is the in situ SST, and n is the number of records at the same dates.

Computations of MHWs and MCSs, as well as their categories of intensity according to Hobday et al. (2018), were calculated using the “heatwaveR” package in R (RCore Team, 2021; Schlegel & Smit, 2018). Descriptive statistics and simple linear regressions were used to explore general trends of MHWs and MCSs per year, selecting categories II (strong), III (severe), and IV (extreme) for our analysis (Hobday et al., 2018; Schlegel et al., 2017). We discarded the use of category I (moderate) events because they are generally common (Hobday et al., 2018). Choropleth maps per *marine ecosystem* were created to identify the spatial patterns of these events in QGIS version 3.14.15. Additionally, category III and IV events were examined using NOAA OISST anomaly maps, calculating the per-pixel SST difference between the period defined by the start and end dates of the event and the same averaged SST days during the period 1982–2020. Data were downloaded and processed in R using the package “rgee” (Aybar et al., 2020).

Finally, we compared MHWs and MCSs categories III and IV with regional surface wind conditions to determine if those events could be explained by wind anomalies. We employed meridional (V10) and zonal (U10) winds 10 m above the surface, downloaded every 6 hr, from the ERA5 reanalysis for the period 1982–2020. The U10 and V10 were daily averaged and daily anomaly maps were constructed from the climatology of each variable from 1982 to 2020. Consequently, wind anomalies were averaged for each MHWs and MCSs. The ERA5

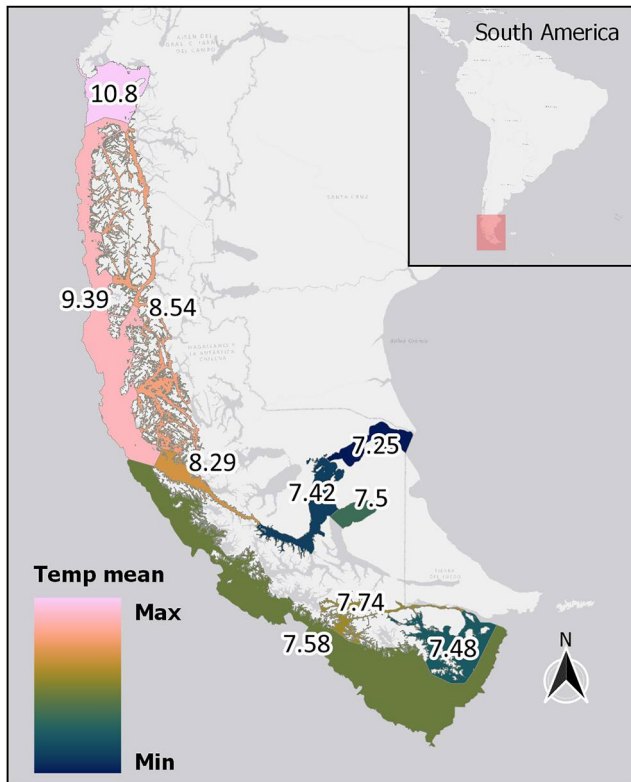


Figure 2. Map of mean sea surface temperature (SST) per marine ecosystem in the period 1982–2020. Each label in the map indicates the mean temperature per marine ecosystem in °C. See Figure 1 for marine ecosystem name. Background map: © OpenStreetMap contributors.

reanalysis is generated by the European Center for Medium-Range Weather Forecast and consists of a global-scale regular grid of 0.25° spatial resolution (Hersbach et al., 2020). Wind data were also downloaded and processed in Python and Matlab, respectively. We used the ERA5 reanalysis because it shows the best agreement with surface wind speed and variability (Ramon et al., 2019).

The extent of the giant kelp forest coverage (Table 3) per ecosystem was computed from a kelp layer derived from Sentinel-2 imagery spanning the period 2015–2019 (Mora-Soto et al., 2020). This layer was clipped per marine ecosystem to obtain an estimate of the total area employing an ellipsoidal WGS-84 datum. We discuss the observed MHW and MCS trends in relation to the main geographical and oceanographic characteristics of each ecosystem and their possible effects on giant kelp forests.

3. Results

3.1. Overview of SST per Marine Ecoregion

The total mean temperature of the complete area of study was 8.2°C, with maximum mean temperature in Gulf of Penas (10.8°C) and minimum mean in Eastern Strait of Magellan (7.3°C), in a descending pattern from north to south and west to east. Daily maximum temperature was 16.7°C in Gulf of Penas (22 January 2016) and minimum temperature was 0.7°C in Western Strait of Magellan (7 July 2015) throughout the entire period of study (Figure 2).

Satellite and in situ SST records show similar values (Table 2, Supporting Information), with moderate to large RMSE (0.46–1.80) and biases ranging between -0.11°C and 0.84°C . Linear regressions were statistically significant ($p < 0.001$), with r-squared values that were larger toward the eastern entrance of the Strait of Magellan (Bahia Gregorio, 0.97) and lower in the sites distanced to the OISST pixels (Puerto Eden, 0.68; Puerto Williams, 0.69). Except for Punta Arenas, all the in situ sites had a positive bias, indicating that the satellite data were slightly higher than the in situ data (i.e., SSTs estimated from satellites tended to be higher than those measured in situ).

3.2. Overview of MHWs and MCSs in Southwestern Patagonia (1982–2020)

3.2.1. Marine Heatwaves (MHWs)

A total of 148 MHWs were detected in the area of study, not including the more common Type I (moderate) events. Among them, 132 were category II (strong), 15 category III (severe), and 1 category IV (extreme). The years with the highest frequency of MHW were 1998 (20), 2020 (15), 2006 (14), and 2016 (13), whereas the years with severe events were 1984 (2), 1998 (8), 2016 (3), and 2020 (2). The recorded extreme MHW occurred in 1984 (Figures 3a and 4a; Supporting Information).

The period with the most severe MHWs occurred in July–September 1998 (austral winter in a strong El Niño year; Carr et al., 2002) and extended over almost all the marine ecosystems of our area of study, from Gulf of Penas to Nearshore Nassau-Hornos, with a maximum intensity of 3.85°C above the climatological mean (Western Strait), and a maximum period of 181 days (Eastern Strait of Magellan). December 1984 (austral spring) was also highly

Table 2
Validation Results for the In Situ Sites, Indicating RMSE, r-Squared and Bias Values

	RMSE	r-squared	Bias
Bahia Gregorio	0.46	0.97	0.21
Caleta Meteor	1.80	0.73	1.30
Punta Arenas	0.57	0.86	-0.11
Puerto Eden	1.07	0.68	0.16
Puerto Williams	1.25	0.69	0.84

Note. All regressions were statistically significant (p -value < 0.001).

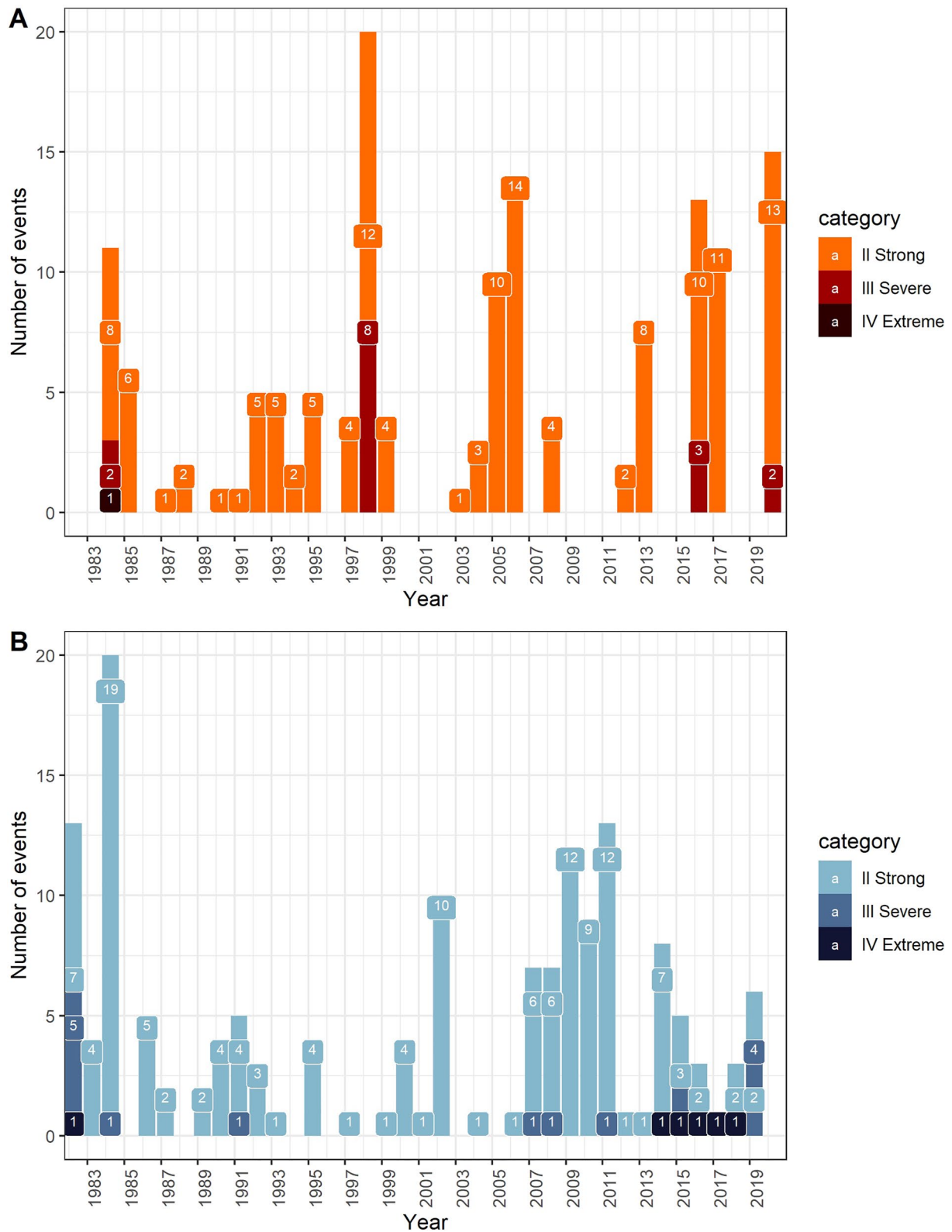


Figure 3. Number of events categories II, III, and IV for the period 1982–2020 for the total of ecosystems in the area of study, for (a) MHWs and (b) MCSs

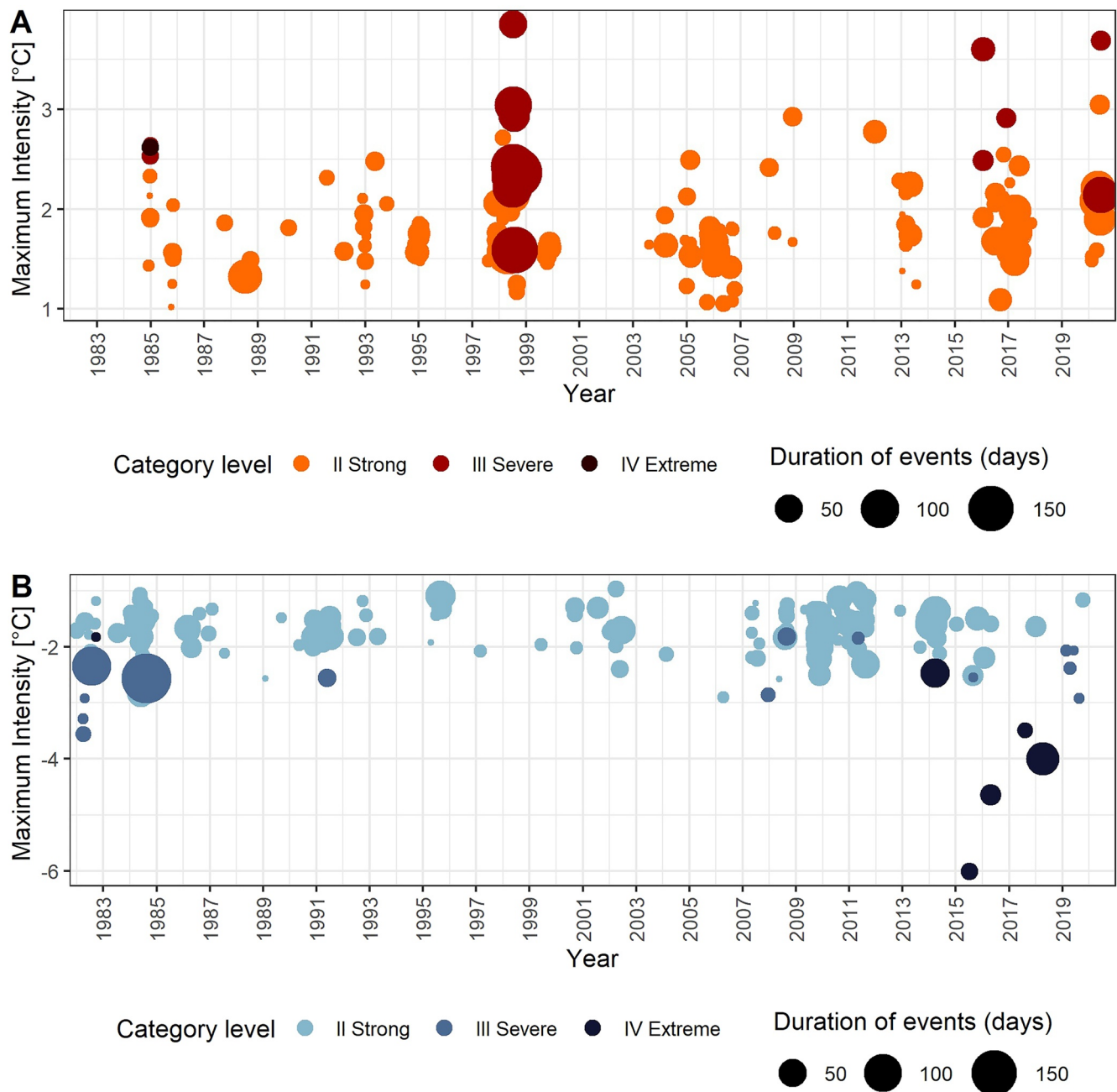


Figure 4. Duration of days of (a) marine heatwaves (MHWs), and (b) marine cold-spells (MCSs), categories II, III, and IV, vs. their maximum intensity (notice that the category is related to the climatological mean of the day of the year)

anomalous, with an extreme event that achieved a maximum intensity (SST anomaly) of 2.6°C and lasted for 16 days (Central Strait of Magellan).

There were no extreme events recorded in the period 1999 to 2020, but severe events were recorded in January 2016 (Offshore Kawésqar and Gulf of Penas) during summer on a strong El Niño year, November 2016 (Gulf of Penas), and June 2020 (Nearshore Beagle Ballenero and Offshore Magallanes). These events lasted for a maximum of 35 days in Gulf of Penas and 88 days in Offshore Magallanes. Choropleth maps (Figure 5) show that most of the MHWs category II occurred near the Gulf of Penas in the northern part of our area of study (Figure 5a), whereas the severe and extreme events were in Gulf of Penas, the offshore areas and the Central Strait (Figures 5b and 5c).

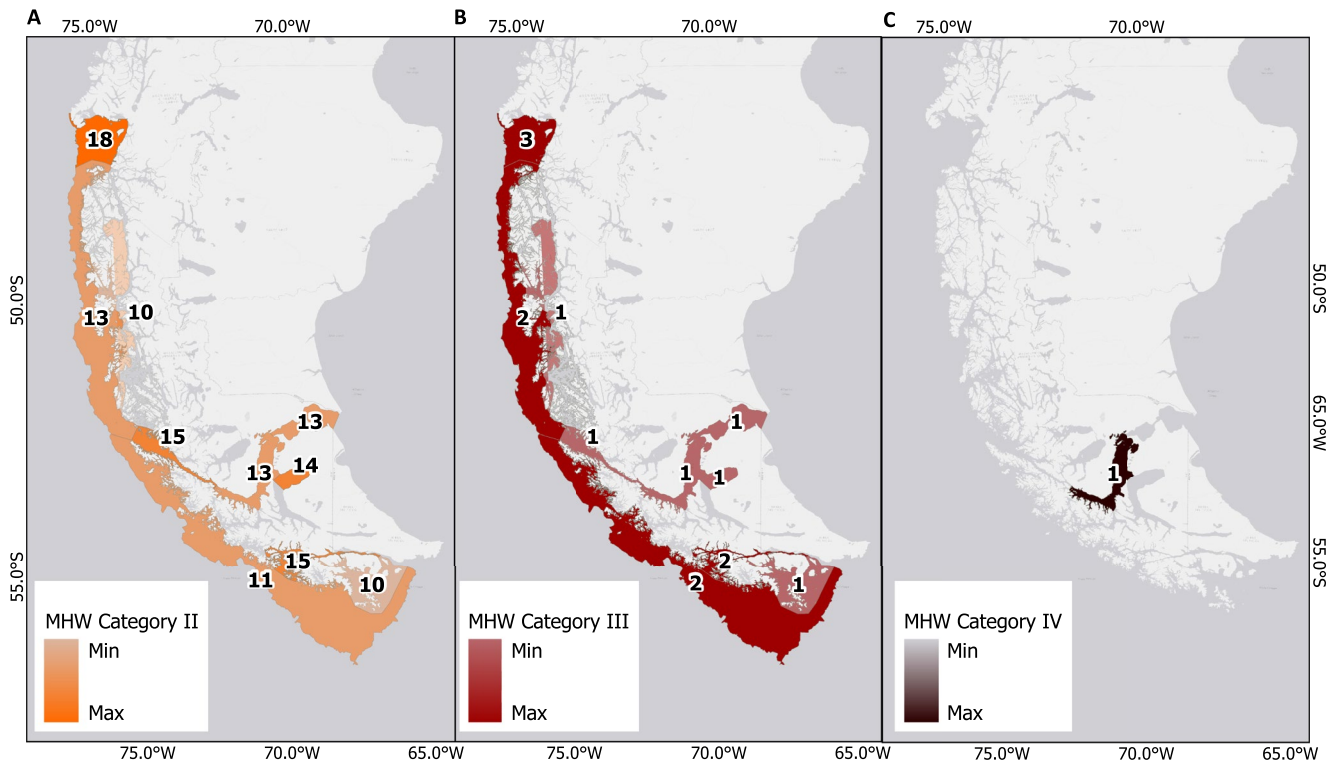


Figure 5. Marine heatwaves (MHWs), period 1982–2020, categories II (a), III (b), and IV (c). Each label in bold indicates the number of events per marine ecosystem. Background map: © OpenStreetMap contributors.

3.2.2. Marine Cold-Spells (MCS)

There were 158 MCSs during the period 1982–2020 in the area of study; 137 category II (strong), 15 category III (severe), and 6 category IV (extreme). The year with the highest frequency of MCS was 1984 (20), followed by 1982 (13), 2011 (13), 2009 (12), and 2002 (10). The years with the most severe events were 1982 (5) and 2019 (4). The years 1982, 2014, 2015, 2016, 2017, and 2018 recorded extreme events. The frequency of these events in the last decade is remarkable in an overall warming planet. Among them, the event of 1982 occurred in Bahía Inútil, and the events from 2014 to 2018 were in Nassau-Hornos (2) and one each in Nearshore Kawésqar, Beagle Ballenero, and Western Strait of Magellan, the latter of which with the event with maximum intensity (-6.01°C) in a relatively short period (16 days). All of these events occurred in the austral fall to winter mid-season (Figures 3b and 4b; Supporting Information).

Choropleth maps show that category II events are concentrated in Nearshore Kawésqar (Figure 6a), and categories III and IV have more presence in the nearshore areas such as Kawésqar, the waters across the Strait of Magellan, Beagle Ballenero and Nassau Hornos (Figures 6b and 6c).

3.2.3. SST, U10, and V10 Anomaly Maps for Severe and Extreme Events

We found four main wind-SST patterns associated with warm and cold severe and extreme events. These are displayed in more detail in Supporting Information (SI).

1. *Cold events with strong winds:* We found events with strong zonal winds (U10) either in their positive (west to east) to negative (east to west) flows, and positive northward winds (V10), in the southernmost ecosystems of Nearshore Nassau-Hornos, Beagle Ballenero, Bahía Inútil, and Western Strait. Among them, the most extreme winds occurred in 2015 (SM.14), 2016 (SM.16), and 2019 (SM.20, SM.21, SM.22, SM.23, Figure 7), and moderate winds associated with positive zonal (U10) flows around the Western Strait (SM.1).

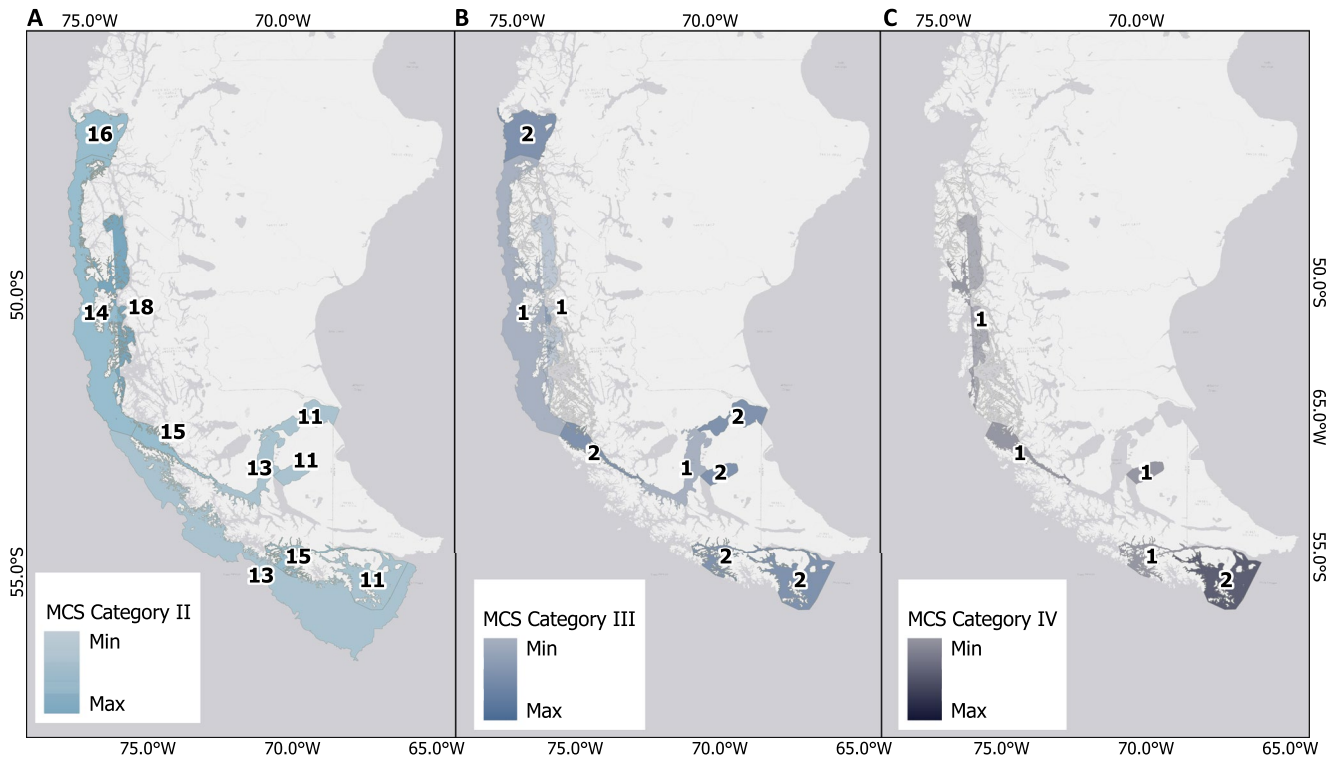


Figure 6. Marine cold-spells (MCSs), period 1982–2020. Categories II (a), III (b), and IV (c). Each label in bold indicates the number of events per marine ecosystem. Background map: © OpenStreetMap contributors.

2. *Cold events without strong winds:* These events have a very localized presence in the interior of the fjords, with extreme spikes in temperature with a duration of less than 5 days. Cold anomalies lasting for two to 3 months in the eastern side of the Strait also occurred unrelated to strong winds. In the first case, the most relevant events occurred in Gulf of Penas (SM.2), Western Strait (SM.9), and Nassau Hornos (SM.12). The latter case occurred in Eastern Strait in 1984 (SM.5).
3. *Warm events with strong winds:* Observed in the warm event of 1984 (SM.6), with strong northward and westward winds (from the continent to the Pacific Ocean). This event was not entirely recorded due to a data gap after the 30 December 1984.
4. *Warm events without strong winds:* Observed in the massive event of 1998 (SM.8), two events in Gulf of Penas and Offshore Kawésqar in 2016 (SM.15, SM17), and Offshore Magallanes and Nearshore Beagle Ballenero in 2020 (SM.24; Figure 8).

On the duration of the warm and cold events, the median and mean duration for severe and extreme MCSs were 11 and 28 days, respectively. Severe and extreme MHWs lasted a median of 57 days and a mean of 72 days. Durations were significantly different (Wilcoxon rank sum test, p -value < 0.01). The longer duration of warm events means that over the study period, severe and extreme warm SST anomalies occurred for a total of 1,166 days, vs. 604 for severe and extreme cold SST anomalies. However, this trend is reversed in the last decade starting in 2011, with a total of 257 days under severe and extreme cold SST anomalies vs. 193 days under warm severe and extreme SST anomalies, despite the longer average and median durations of MHWs.

In general, both MCSs and MHWs are more related to anomalies in local wind speed and/or wind direction when they have a synoptic duration, that is, less than 10 days. In that case, exceptional wind speed can modify air-sea heat fluxes and near-surface mixing, while uncommon wind direction can change surface ocean circulation impacting SSTs. On the other hand, during longer MCSs and MHWs, local surface wind speed and wind direction show values along with their complete range of distribution, suggesting that longer scale (intraseasonal) MHWs and MCSs would have an oceanographic forcing rather than a local atmospheric forcing.

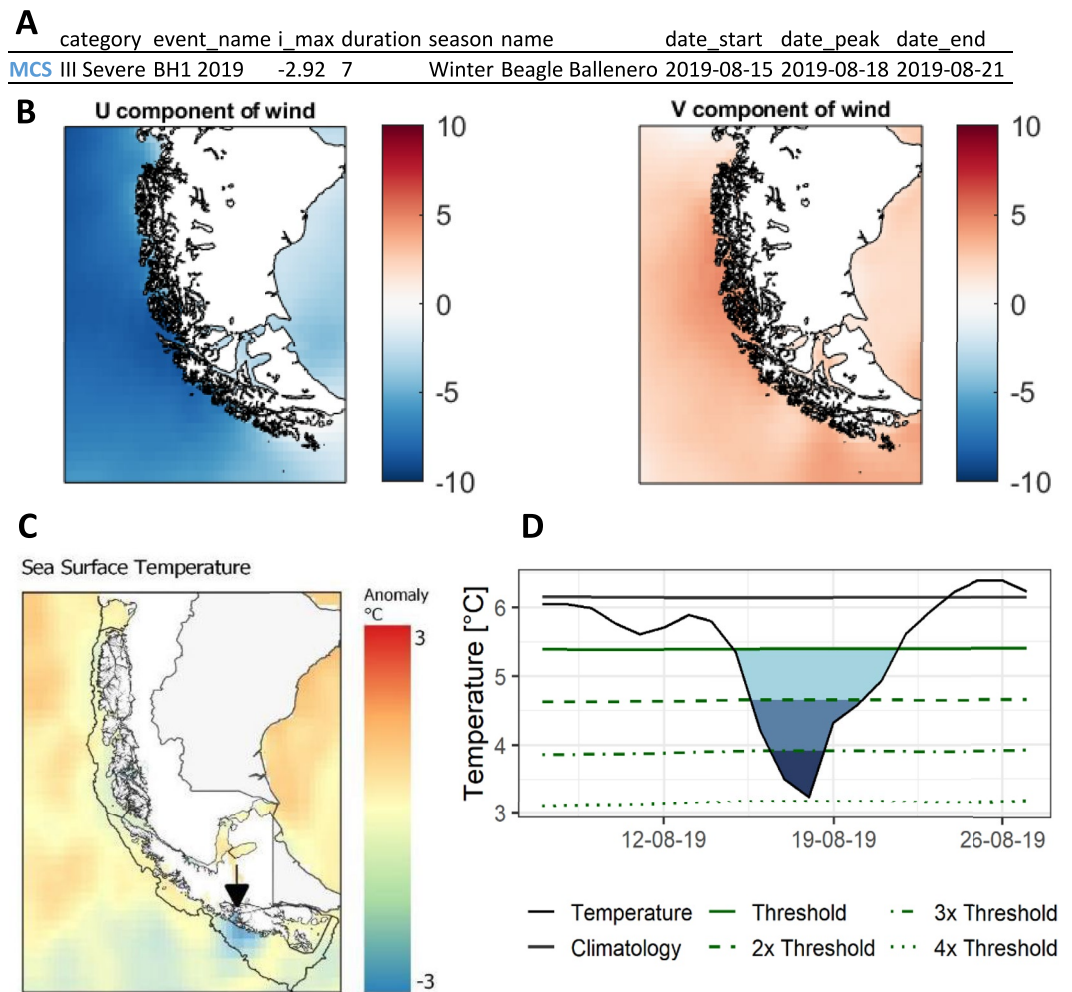


Figure 7. An illustration of a marine cold-spell (MCS) with strong winds: Nearshore Beagle Ballenero 2019. (a) Category, name of the event, maximum intensity ($^{\circ}\text{C}$), duration (days), season, name of the ecosystem, start, peak, and end dates. (b) Anomaly maps of the eastward (U10) and northward (V10) winds 10 m above the surface (m/s), from the ERA5 reanalysis. (c) Sea surface temperatures ($^{\circ}\text{C}$) computed from the OISST model. Each anomaly map is a mean from the start to the end dates covering a timespan from 1982 to 2020. Ecosystems in focus are indicated with black arrows. (d) Plot of the largest intensity of the series, considering the start, peak, and end dates of each event. (The complete series is in Supporting Information)

4. Discussion

4.1. Satellite Versus In Situ Data

In the complete area of study, three validation sites in the immediate vicinity of OISST pixels exist, plus two more validation sites at a considerable distance to the satellite records. Despite this, the levels of error and bias are in line with previous studies (Lee & Park, 2020; Stobart et al., 2015), which is something to be expected for global SST data adjacent to coastlines. The larger RMSE of Caleta Meteoro (1.80) and Puerto Williams (1.25) may be explained by the complex coastline and bathymetry of the Pacific side of the Strait of Magellan and the turbulent waters around the Cape Horn, which contributed to an increased variability in the data. Our analysis of MHWs and MCSs using SST maps showed a general spatial autocorrelation of the events, largely discarding the effect of noise on the record.

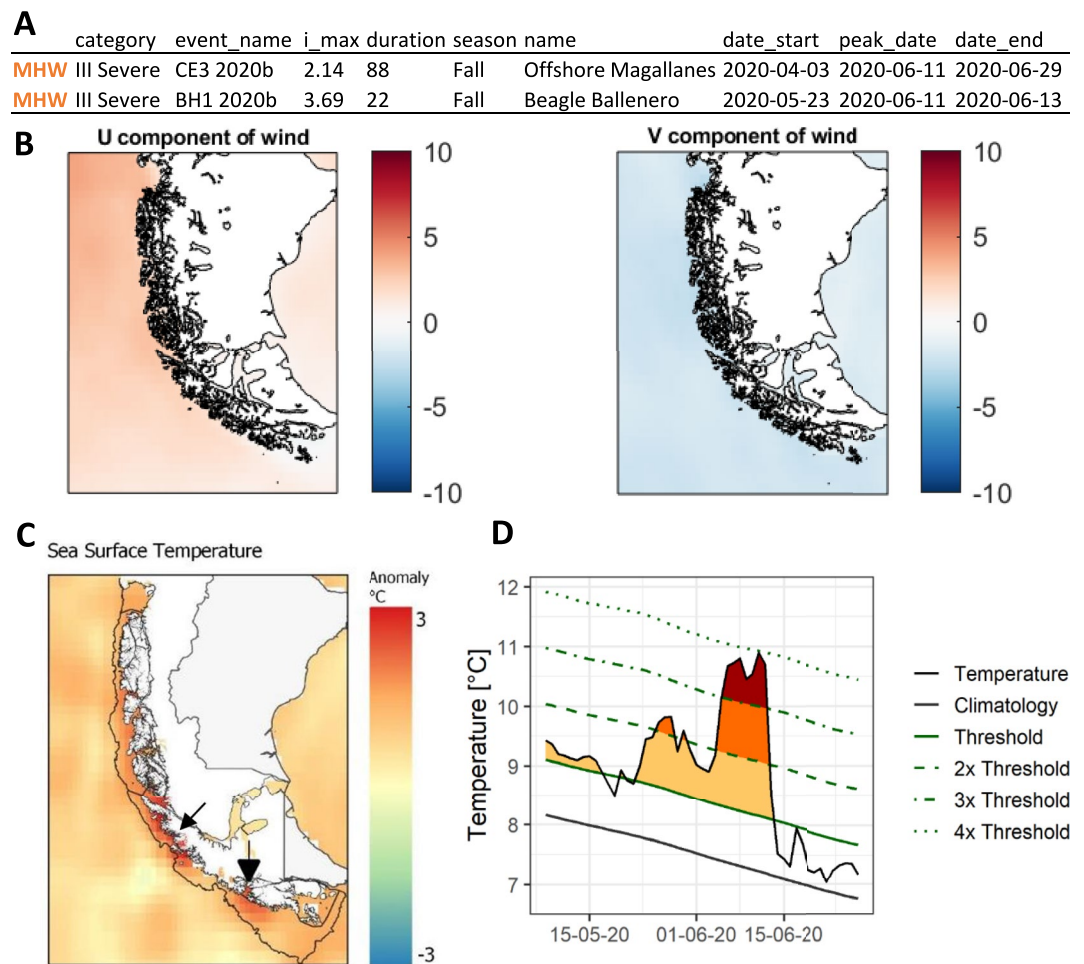


Figure 8. An illustration of an MHW without strong winds: Offshore Magallanes and Nearshore Beagle Ballenero 2020. (a) Category, name of the event, maximum intensity ($^{\circ}\text{C}$), duration (days), season, name of the ecosystem, start, peak, and end dates. (b) Anomaly maps of the eastward (U10) and northward (V10) winds 10 m above the surface (m/s), from the ERA5 reanalysis. (c) Sea surface temperatures ($^{\circ}\text{C}$) computed from the OISST model. Each anomaly map is a mean from the start to the end dates covering a timespan from 1982 to 2020. Ecosystems in focus are indicated with black arrows. (d) Plot of the largest intensity of the series, considering the start, peak, and end dates of each event. (The complete series is in Supporting Information)

4.2. Observations on MHWs and MCSs

The lack of extreme warm events in the last two decades confirms the main trends of low frequency and intensity of MHWs in this region (Marin et al., 2021; Oliver et al., 2018). Moreover, Gulf of Penas is the marine ecoregion with the largest quantity of warm events in the study region: 18 categories II and 3 category III MHWs in four decades, which is in itself a much lower frequency of MHWs than many other regions across the planet (Marin et al., 2021).

The observed distribution of MCSs in the decade of 2010–2020 in western Patagonia shows patterns of spatially constrained nearshore distributions, in line with previous research from South Africa and Western Australia (Feng et al., 2021; Schlegel et al., 2017). However, the South African and Western Australian studies indicate temporal short-term sequences of cold and warm events, whereas in Patagonia this pendular oscillation was only observed in 1982–1984, with a series of cold events in 1982 followed by a series of warm events in 1984. In the decade of 2010s, there was a series of three warm severe events in 2016 in the northern and ocean-exposed part of the study area (Gulf of Penas and Offshore Kawęsqar; SM.15 and SM.17), but the extreme cold event occurred in the southernmost marine ecosystem (SM.16). Regarding the method used to detect and classify MHWs and MCSs (Hobday et al., 2016, 2018), a lower threshold period to detect severe and extreme MCSs using less than

Table 3

Summary of Possible Effects on Giant Kelp Forests by Marine Ecosystem, According to Geographical Characteristics and Warm and Cold Events Observed in This Study

Marine ecosystem	Giant kelp area (hectares)	Main geographical and oceanographical features	Main research gaps on giant kelp forests (open research questions)
Nearshore Kawésqar (N)	67,874	Southern Patagonia Icefield; glacio-nival freshwater input (Meier et al., 2018) Channels and fjords system	Expansion to new deglaciated areas (Wernberg et al., 2019); Increased glacial turbidity; Increased photobiotic stress (Palacios et al., 2021); increased sensibility to low salinities, turbidity, and light limitation (Buschmann et al., 2006; Dayton, 1985)
Beagle Ballenero-Magellan (N)	27,528	Cordillera Darwin Icefield; glacio-nival freshwater input (Bown et al., 2014)	severe and extreme storms carrying cold, nutrient-rich water favorable for giant kelp.
Gulf of Penas (O)	3,109	Northern Patagonia Icefield; glacio-nival freshwater input (Meier et al., 2018). Strong freshwater influence in nearshore and oceanic regions (Galan et al., 2021)	
Exposed coast- Kawésqar (O)	62,438	Windward side of the continent; extreme rainfall (Schneider et al., 2003)	Increased turbulence; nutrient mixing; shorter lifespan of the canopies due to more frequency of storms (Van Tussenbroek, 1989)
Exposed coast- Magellan (O)	77,103	Windward side of the continent; extreme rainfall (Schneider et al., 2003)	
Central Strait of Magellan (N)	11,621	Orographic threshold from the windward (Pacific) to the leeward sides of Patagonia. Deep mixed layer depth.	Increment of the frequency of strong winds.
Bahia Inutil Strait of Magellan (N)	1,376	Shallow waters; rain shadow (Schneider et al., 2003)	
Eastern Strait of Magellan (N)	409	First Narrow to the Atlantic Ocean; high tidal amplitude. Shallow depths, fine grain sediments; Atlantic Ocean influence	Increment of the frequency and intensity of SST anomalies in intertidal environments.
Nassau Hornos-Magellan (N)	72,214	Cape Horn Archipelago and Hardy Peninsula, open areas facing the Southern Ocean	Severe and extreme storms (Winckler et al., 2020); increasing detachment, canopy removal (Seymour et al., 1989), simplifying food webs (Byrnes et al., 2011; Ebeling et al., 1985) and floating kelp rafts (Hinojosa et al., 2010; Reed et al., 1988). Advection of cold, nutrient-rich water favorable for giant kelp.
Western Strait of Magellan (N)	29,741	Windward side of the continent; extreme rainfall (Schneider et al., 2003); Pacific Ocean influence; entrance of the Pacific toward the Atlantic Ocean.	

Note. N, Nearshore. O, Offshore. Giant kelp area was calculated using the map of Mora-Soto et al. (2020).

5 days could help to identify pulses of cold freshwater entering the fjord system with more precision, in a similar way as other studies had refined methods to detect coastal upwelling (Abrahams et al., 2021).

Contemporary trends between 1980 and 2015 in the Chilean coastal zone show that southward 45°S, there has been an increment of wind speed and wave heights accompanied by a negative trend on atmospheric sea level pressure, which itself has been linked to a positive trend in the Southern Annular Mode and, in a minor way, to the Pacific decadal oscillation (PDO; Winckler et al., 2020). The increase in zonal and meridional winds—causing advection of cold surface waters from higher latitudes—could be a possible cause of severe cold events in the southernmost marine ecoregions facing the south of the Pacific Ocean, whereas SST on the eastern side of the Strait seemed to be less affected by wind. This phenomenon has been analyzed at global scale on the Southern Ocean by Schlegel et al. (2021), who reports an increased duration of days for MCSs along with decreases in intensity, also related with wind-induced processes. The present study thus generally agrees with these observations, with the difference that some of our detected events were not induced by wind, mostly in nearshore areas. An implication of these results is that more nearshore studies on MHWs and MCSs are needed considering the local oceanographic and coastal environments.

In the nearshore area of the fjords and channels, SST is generally colder than deep water. This is caused by low salinity and cold continental freshwater layer (freshwater from melting glaciers) over a deep oceanic water layer (Subantarctic Surface Water—SAAW), forming the Modified Subantarctic Water which forms a permanent vertical haline stratification (Iriarte, 2018; Valdenegro & Silva, 2003). During spring and summer months, light

penetration increases throughout the water column, increasing net primary production, as well as CO₂ absorption in the fjords (González et al., 2013; Iriarte et al., 2014; Torres et al., 2011; Vergara-Jara et al., 2019). The presence of very cold-waters in fall and winter causing extreme MCSs in the nearshore areas and not associated to wind anomalies could be explained by increased glacier melting and cold surface water advection and stratification (Iriarte, 2018; Torres et al., 2011), as it seems to be indicated by the generalized retreat of the glaciers in the ecoregion (Meier et al., 2018). We infer that this may be the reason behind the relatively short span of the extreme cold events in the fjords area, in contrast with the longer duration of the warm events which seem to be related with offshore oceanographic oscillations, such as El Niño in 1998 and 2016 (Garreaud, 2018). Additionally, the warm event of 1984, associated with strong winds, occurred during a La Niña year, as did the warm events of 2020. More research is required on the possible mechanisms that link La Niña and warm SST in this region.

4.3. Giant Kelp Forests in Patagonia: A Climatic Refugium With New Stressors

Previous studies have been carried out on the negative effects of MHWs in communities, distribution, and resilience of giant kelp forests along the temperate coastlines of the Pacific Ocean (Arafah-Dalmau et al., 2019; Beas-Luna & Ladah, 2014; Cavanaugh et al., 2019; Smale, 2019; Wernberg et al., 2016, 2013). In contrast, this work is a first approach to identify sea temperature trends in the sub-Antarctic region of Patagonia. In this study, we have identified that during the 1982–2020 period, maximum temperatures—even with MHWs—stayed below 15°C–17°C, the temperature threshold above which giant kelp shows a decline in germination and growth (Buschmann et al., 2004, 2014; Fernández et al., 2021). The positive bias in the remotely sensed SST data (Table 2) imply that these are conservative estimates and thus add weight to the lack of occurrence of SSTs above 15°C–17°C in the region for the observed period.

Given the observed trends in MHWs, MCSs, and SST in the study area, the interplay between dynamic forcing (wind-caused cold-water advection and mixing) and fresh-water inputs seem to be very efficient in keeping SST trends in check; however, warm events driven by ENSO tend to be long-lasting (more than 1 month) in the area, causing possible thermal stress in these ecosystems. Overall, Patagonia might be a climatic refugium for giant kelp. This however does not release this ecosystem of other environmental stressors, all of them new frontiers for kelp studies.

In intertidal environments, macroalgae are subjected to constant variations of abiotic factors that can cause a detrimental effect on their photosynthetic performance, that is, high variations in the quality and quantity of incident irradiance (Cruces et al., 2017) or depth gradients (Koch et al., 2016). However, the remarkable adaptive capacity of giant kelp allows this species to thrive at diverse environments up to some limits (Dayton, 1985; Graham et al., 2007). In this context, cold temperatures are also a limiting environmental factor, which can restrict the biogeographic distribution of macroalgae of the order Laminariales at polar latitudes (Pellizzari et al., 2020). This thermal condition, together with irradiance, are key in the reproductive success of gametogenesis in female gametophytes (Deysher & Dean, 1986; Ladah & Zertuche-González, 2007).

On the other hand, sediments in the water column coming from melting glaciers can increase water turbidity and block light, hence becoming a possible stressing factor for the photosynthetic performance of giant kelp sporophytes. However, a recent study conducted in a fjord with marked glacier retreat in southern Tierra del Fuego with elevated seasonal turbidity (Huovinen et al., 2019) showed that giant kelp has a strong adaptability in their photobiological traits to this environmental change (Palacios et al., 2021).

Current trends in the study region could mean favorable conditions for giant kelp as foundation species for a multitude of organisms (Friedlander et al., 2020, 2018, 2021; Rios & Mutschke, 2009) but additional stressing factors on giant kelp can be increased UV radiation, reduced salinity, and ice cover, increased runoff and turbidity (Filbee-Dexter et al., 2019; Huovinen et al., 2019), or extreme turbulence in exposed offshore causing high canopy removal (Van Tussenbroek, 1989) and increasing the competition for light for subtidal algae (Bartsch et al., 2016) or colonization of new spaces (Bolton et al., 2012; Krumhansl et al., 2016; Palacios et al., 2021). Finally, as an anthropogenic factor, the presence of introduced species as salmon farms in the area could mean indirect effects on giant kelp, not yet studied (Friedlander et al., 2021).

We outline possible effects of these events on giant kelp by ecosystem in Table 3. All of them are yet unanswered research questions that require further development. Overall, we hypothesize that nearshore areas closer to the fjords will be more affected by freshening due to glacier melting; exposed areas will be more affected by a higher

frequency of strong winds and storms, and areas facing the polar front could be favored by the presence of cold and nutrient-rich waters.

5. Conclusion

Western Patagonia has experienced a high frequency of extreme cold events in the decade of 2010–2020 that could be explained by cold-water inputs in the fjords area, as well as strong wind anomalies delivering cold-water from the higher latitudes in the region from the western entrance of the Strait of Magellan to the Cape Horn Archipelago, in line with previous analysis that have indicated a cooling trend in the Southern Ocean. We also identified warm events that could be explained by the wider-range oscillations of El Niño and La Niña, but were not as short and extreme as the cold events. There are still many unanswered questions about the mechanisms behind the occurrence of cold events, and nearshore analyses of MHWs and MCSs at finer scales are important topics for future research.

As cold-water temperature is a positive factor for giant kelp, this trend gives support to previous observations of the long-term persistence of this important marine ecosystem in this ecoregion. However, increased freshwater inputs and turbulence from enhanced cold-water advection could mean additional stressing factors for giant kelp. We identify research lines to address the wider range of possible stressors that the giant kelp ecosystem may face, such as freshwater inputs from glacier melting and increased storms and turbulence.

Data Availability Statement

The MHW and MCS data sets generated during the current study are available in the following repository: <https://doi.org/10.5061/dryad.905qftm5>.

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